Use of a Microwave Cavity for Sensing Dielectric Properties of Arbitrarily Shaped Biological Objects

ANDRZEJ W. KRASZEWSKI, MEMBER, IEEE, STUART O. NELSON, SENIOR MEMBER, IEEE, AND TIAN-SU YOU

Abstract —A rectangular waveguide resonator operating in the H_{103} mode at 3.2 GHz was used in determining the change in resonant frequency, ΔF, and the Q factor of the cavity, ΔT, when measured with and without single corn kernels of various shapes and dimensions. By measuring those variables for a kernel oriented in two positions, differing by a 90° rotation with respect to the maximum E-field vector, the average values of ΔF and ΔT were found to be quite independent of shape. The ratio $\Delta F/\Delta T$ is independent of size and is a function of the material properties $(\epsilon'-1)/\epsilon''$. This function is shown to be related to the material density, the moisture content, or other characteristics when all other properties except the one selected remain unchanged.

I. Introduction

CONVENTIONAL electronic instruments for moisture content determination in grain and seed provide a moisture content reading which is an average for all kernels in a sample (e.g. 100 g or more) [1]. There is a need for an instrument that can determine the moisture content of individual kernels within samples.

Recently, concern has developed that spoilage of grain in transit or storage may be related to the practice of mixing high-moisture grain with lower-moisture grain to meet an average moisture content upper limit. Thus, an instrument that could determine the moisture content of individual kernels within samples would be useful for detecting blended lots of grain. Some success has been achieved in detecting single-kernel moisture content by conductivity measurements on grain kernels passing between a pair of crushing-roller electrodes [2] and by impedance measurements on individual corn kernels with capacitive sensors at radio frequencies [3].

Resonant cavity techniques are widely used in measuring the microwave properties of materials [4] by measuring the shift in the resonant frequency and the change in the Q factor of the cavity when the sample is inserted into the cavity. This technique may provide an interesting alternative to the existing methods for kernel moisture determination because it offers nondestructive and relatively fast measurements. On the other hand, difficulties include the fact that the measured parameters are dependent on the volume, geometry, and mode of operation of the cavity and on the permittivity, shape, dimensions, and location of the object inside the cavity [5], [6].

The purpose of this research was to determine the effect of corn (*Zea mays L.*) kernels of various shapes and dimensions and different hydration levels on the parameters of a resonant cavity operating at a microwave frequency and to evaluate the feasibility for moisture content determination in individual corn kernels. The promising results obtained for soybean seeds, which are nearly spherical in shape [7], provided a basis for continuing the research with corn kernels. As concluded in the previous report [8], the experiments should be carried out at a frequency lower than 6 GHz. This paper presents the results obtained with a cavity resonating at 3.2 GHz.

II. Materials and Methods

A. Corn Kernels

The corn kernels used were from six hybrid, yellow-dent field corn cultivars grown in four different states in 1988, harvested at high moisture levels, and stored at 4°C after harvest. In contrast to soybeans, corn kernels are highly nonuniform, irregularly shaped objects, sometimes pyramidal, cuboidal, or disklike; they are up to 14 mm long, with no plane surfaces and seldom with surfaces parallel to each other. The maximum-to-minimum dimension ratio ranged from 1.25 to 4. One hundred and four kernels were selected from six lots with initial moisture contents of about 18%, wet basis. Among these kernels, the highest-to-lowest weight ratio was 2.1. Between microwave cavity measurements, the kernels were permitted to dry under room conditions (23°C, 30% RH) for various time intervals and were then sealed in glass vials and held at 4°C for at least 24 hours prior to measurement to obtain more uniform moisture distributions within the kernels. They were weighted after each microwave measurement to an accuracy of 0.2 mg and finally were dried in a forced-air oven at 103°C for 72 hours to determine the

Manuscript received November 6, 1989; revised March 6, 1990.
A. W. Kraszewski and S. O. Nelson are with the Richard B. Russell Agricultural Research Center, Agricultural Research Service, U.S. Department of Agriculture, Athens, GA 30613.
T. You was with the Richard B. Russell Agricultural Research Center, Agricultural Research Service, U.S. Department of Agriculture, Athens, GA 30613. He is now with the Department of Radio Electronics, Zhejiang University, Hangzhou, People's Republic of China.
IEEE Log Number 9036150.

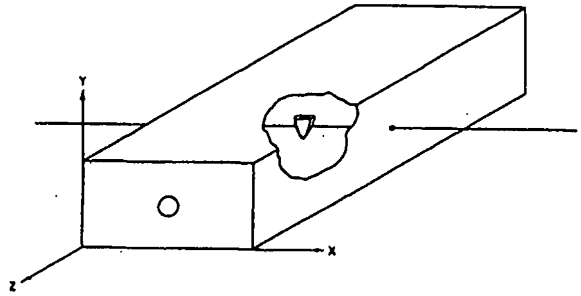


Fig. 1. Corn kernel located at the center of a rectangular waveguide cavity operating in the H_{105} mode.

dry weight. The moisture content of each kernel at the time of microwave measurement was then calculated to complete the calibration. The same procedure was later applied to 80 kernels used as a verification sample set.

B. Measuring Arrangement

A 0.33 mm nylon line was passed through the individual kernels, permitting them to be held in the center of a rectangular cavity and rotated accurately about the x axis (Fig. 1). The cavity consisted of a section of standard WR-284 waveguide (inside dimensions, 72×34 mm^2) 305 mm long and was coupled with the external waveguides through two identical holes 20.6 mm in diameter. The resonant frequency of the empty cavity operating in the H_{105} mode was 3205.8 MHz and its Q factor, Q_{L0} was 1650.

The cavity was located between two waveguide-to-coaxial transitions, which allowed it to be connected to an automatic network analyzer calibrated in the transmission mode. The analyzer took 801 discrete frequency points with a range of 8 MHz spanning the resonant frequency of the cavity. This allowed measurement of the transmission through the cavity in increments of 10 kHz by reading the coordinates of a marker position. A "marker to maximum" command automatically accomplished the determination of the resonant frequency with an accuracy better than 5 kHz and the transmission coefficient (S_{21}) through the cavity with an accuracy of 0.02 dB.

In the following experiments, the shift of the resonant frequency is denoted by $\Delta F = f_0 - f_s$, where the subscripts 0 and s refer to the empty cavity and the cavity loaded with a seed at the center of the cavity, respectively. Energy dissipated in the object is expressed as a change in the cavity Q factor:

$$\frac{1}{Q_{Ls}} - \frac{1}{Q_{L0}} = \frac{1}{Q_{L0}}\left(\frac{V_0}{V_s} - 1\right) = \frac{\Delta T}{Q_{L0}}.$$

Here V denotes the voltage transmission coefficient at resonance, $\Delta T = (10^k - 1)$ is the transmission factor, and $k = 0.05\,(S_{210} - S_{21s})$, with S_{21} being the voltage transmission coefficient at resonance, expressed in decibels.

III. General Considerations

The resonant cavity parameters with a kernel located at the center of the cavity are related to the kernel material permittivity, $\epsilon = \epsilon' - j\epsilon''$, the kernel volume, and the kernel shape by the expressions [5], [6]

$$\Delta F = (\epsilon' - 1) K f_0 \left(\frac{v_s}{v_c}\right)$$

and

$$\Delta T = \epsilon'' K^2 Q_{L0} \left(\frac{v_s}{v_c}\right) \tag{1}$$

where v_c is the volume of the empty cavity (749 cm^3), v_s is the volume of the object, and K is the shape factor, accounting for all effects related to the shape of the object. The ratio of these two quantities,

$$X = \frac{\Delta F}{\Delta T} = \frac{(\epsilon' - 1)}{\epsilon''}\frac{C}{K} \tag{2}$$

is a size-independent function of the material permittivity and the shape of the object, where $C = f_0 / Q_{L0}$ is a constant dependent on the parameters of the empty cavity. When all objects to be measured are of similar shape [7], small variations in K cause variations in X which are comparable to the system measurement errors. X is then a size- and shape-independent function.

Since corn kernels are nonuniform and irregularly shaped, the value of K in (2) may differ by more than a factor of 2. However, it has been observed [8] that when a kernel is rotated about the x axis of the cavity, both ΔF and ΔT show variations proportional to $\cos^2\theta$, where θ is the angle of rotation. As shown in Fig. 2 for two kernels of different sizes and shapes but with the same moisture content, 16.4%, the measured values of ΔF and ΔT variations have the same character. The amplitude of the variation is smaller for the larger, nearly spherical kernel A (maximum-to-minimum dimension ratio of 1.27), than for the flat, disklike kernel B (ratio of 2.20), but the ratio of averaged values is similar for the two kernels (6.32 and 6.26).

To examine the relationships shown in Fig. 2 in more detail, the extremum values of ΔF and ΔT were measured for many kernels rotated in the cavity. Results for several kernels of similar moisture contents, 13%, and of almost constant maximum-to-minimum dimension ratios (ranging from 2.8 to 3.3), but of different sizes, are shown in Fig. 3. The minimum, the maximum, and the averaged values of the resonant frequency shift and the transmission factor are linear functions of the wet kernel weight. The ratio of the two averaged values, $X = \Delta F_{avg} / \Delta T_{avg}$, remains virtually constant, independent of the size of the kernel, as shown in Fig. 4.

The extremum values of the cavity parameters for kernels of almost constant weight (0.275–0.295 g) and moisture content (13.0 ± 0.25%), but of different shapes, are presented in Fig. 5. A dimension ratio of 1 corresponds to

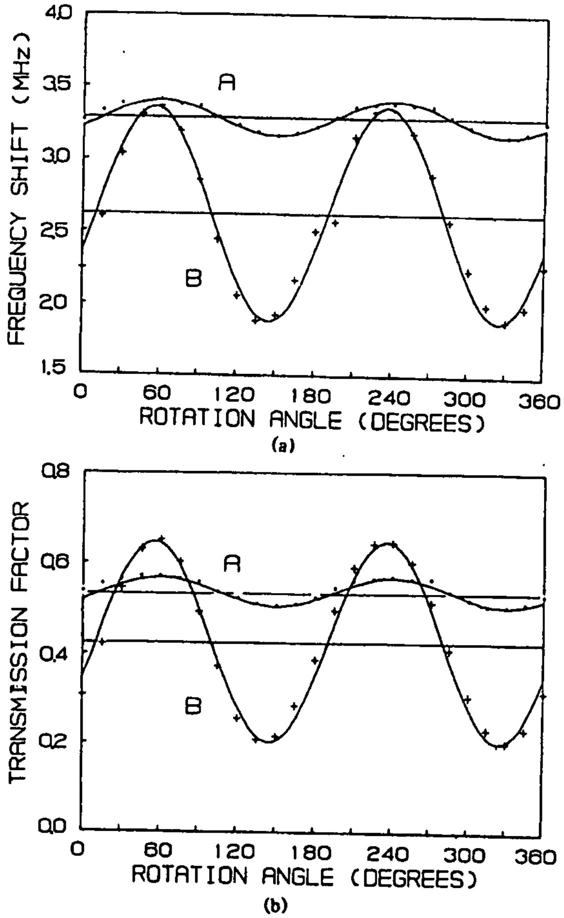


Fig. 2. Resonant frequency shift, ΔF, and transmission factor, ΔT, as a function of kernel orientation for two kernels of different shape and size but similar moisture content.

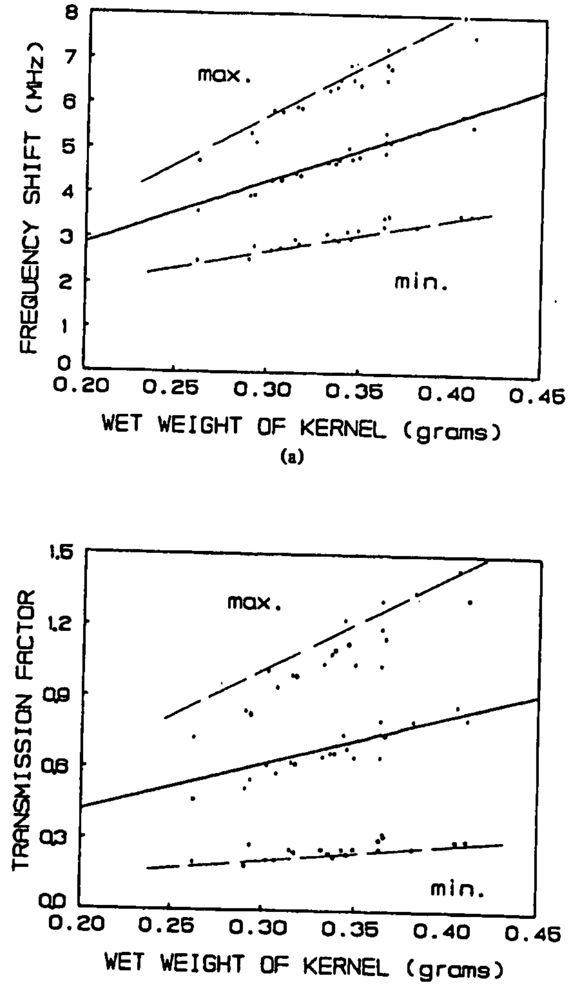


Fig. 3. Resonant frequency shift, ΔF, and transmission factor, ΔT, as a function of wet kernel weight for several kernels of similar shape (dimension ratios 2.8 to 3.3) and moisture content (13% w.b.).

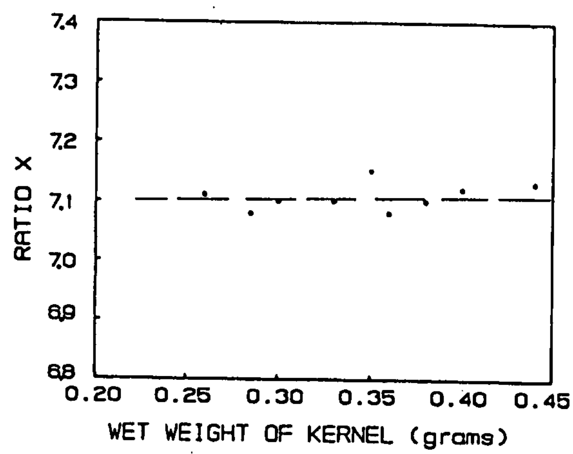


Fig. 4. Ratio of the two averaged quantities from Fig. 3, $\Delta F_{avg}/\Delta T_{avg}$, as a function of wet kernel weights. All kernels had similar dimension ratios and moisture contents.

spherical kernels, while a dimension ratio of 3 or more corresponds to flat, disklike kernels. None of the measured extremum values change linearly with the dimension ratio, but the ratio of the averaged quantities is nearly independent of the dimension ratio, as shown in Fig. 6. Similar relationships were obtained for groups of kernels of various sizes and shapes and different hydration levels.

These observations may be explained as follows: for two measurements with a kernel rotated by 90°, one obtains

$$\Delta F_1 = (\epsilon' - 1) K_1 f_0 \left(\frac{v_s}{v_c} \right)$$

$$\Delta T_1 = \epsilon'' K_1^2 Q_{L0} \left(\frac{v_s}{v_c} \right) \tag{3a}$$

and

$$\Delta F_2 = (\epsilon' - 1) K_2 f_0 \left(\frac{v_s}{v_c} \right)$$

$$\Delta T_2 = \epsilon'' K_2^2 Q_{L0} \left(\frac{v_s}{v_c} \right) \tag{3b}$$

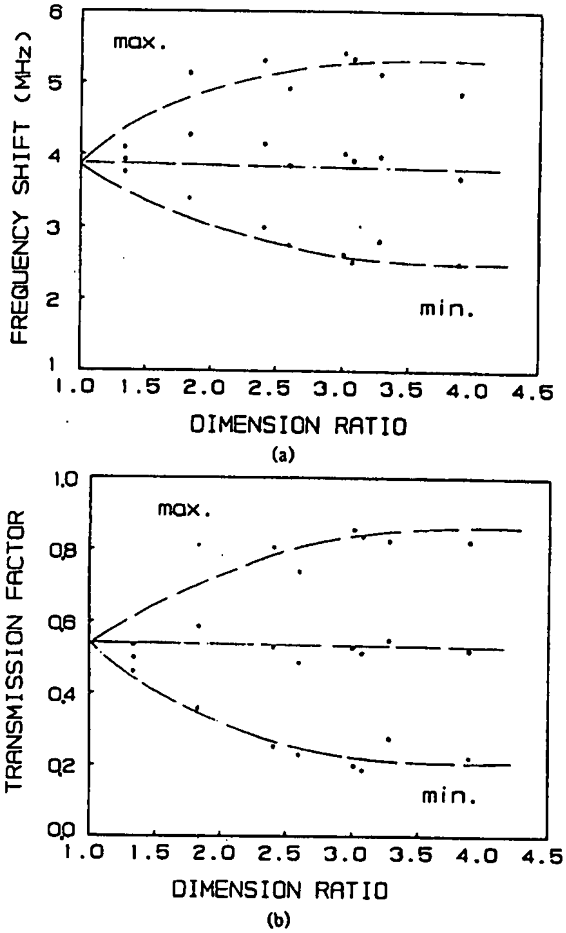


Fig. 5. Resonant frequency shift, ΔF, and transmission factor, ΔT, as a function of kernel dimension ratio for several kernels of similar size (wet weight from 0.275 g to 0.295 g).

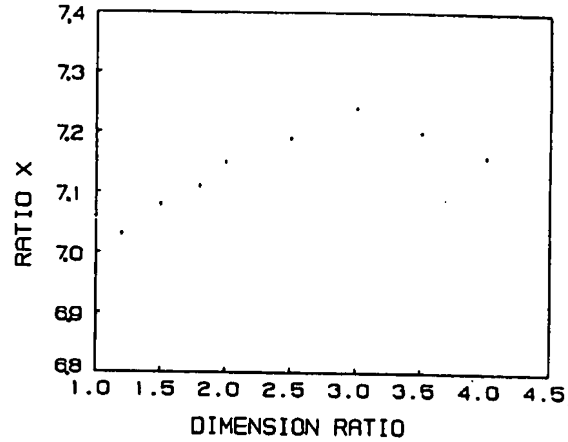


Fig. 6. Ratio of the two averaged quantities from Fig. 5, $\Delta F_{avg}/\Delta T_{avg}$, as a function of kernel dimension ratio.

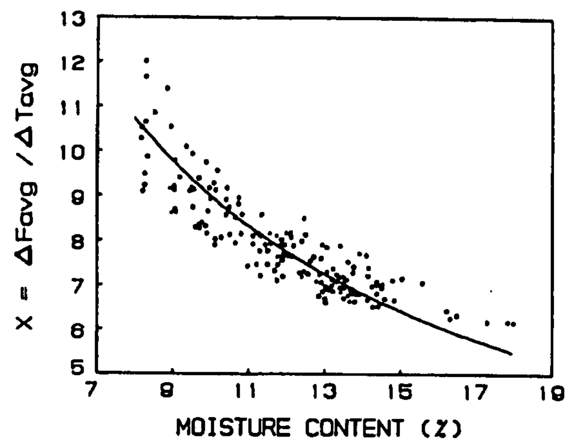


Fig. 7. Parameter X as a function of moisture content for corn kernels. Solid line is calculated from eq. (6).

where the shape factors K_1 and K_2 are related to their extremum values:

$$K_1 = K_{min} + (K_{max} - K_{min})\cos^2\theta$$

$$K_2 = K_{min} + (K_{max} - K_{min})\cos^2(\theta \pm \pi/2).$$

Taking the average of the two measured values, one has

$$\Delta F_{avg} = \frac{\Delta F_1 + \Delta F_2}{2} = \frac{1}{2}(\epsilon' - 1)(K_1 + K_2) f_0\left(\frac{v_s}{v_c}\right)$$

$$\Delta T_{avg} = \frac{\Delta T_1 + \Delta T_2}{2} = \frac{1}{2}\epsilon''(K_1^2 + K_2^2) Q_{L0}\left(\frac{v_s}{v_c}\right) \quad (4)$$

which leads to the size-independent function as before (2),

$$X = \frac{\Delta F_{avg}}{\Delta T_{avg}} = \frac{(\epsilon' - 1)}{\epsilon''}\frac{C}{K_{eff}} \quad (5)$$

where

$$K_{eff} = \frac{K_1^2 + K_2^2}{K_1 + K_2}.$$

As in the case of soybeans [7], the function is highly correlated with moisture content in corn kernels.

IV. Experimental Results

Experimental results for the 104 kernels measured at various hydration levels to give 161 data points are shown in Fig. 7. The calibration equation fitting the experimental data has the simple form

$$M = \frac{112}{X} - 2.45 \quad (6)$$

and a correlation coefficient $r = 0.878$.

To test the validity of the calibration equation (6), another 80 corn kernels were randomly selected from the same lots. This sample had a highest-to-lowest dry weight ratio of more than 2. Cavity measurements were taken over the moisture content range from 9% to 17%. Their exact moisture contents were determined by the standard oven method and compared with those calculated from (6). The histogram shown in Fig. 8 presents the distribution of differences between oven moisture content and calculated moisture content for 80 data points. The mean

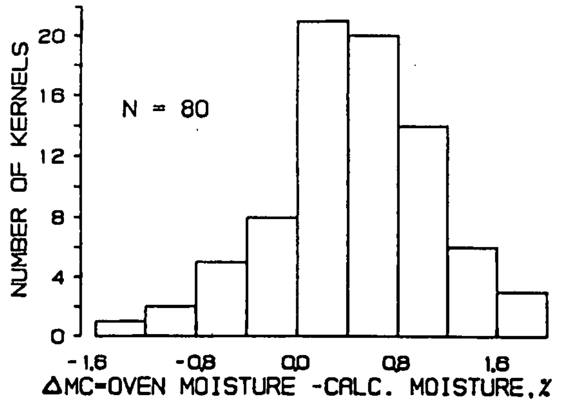


Fig. 8. Distribution of differences between oven moisture content determination and moisture content calculated from calibration eq. (6).

value of the difference was 0.44% moisture and the standard deviation of the difference was 0.64% moisture. Therefore, the calibration equation (6) can be used to determine the moisture content of corn kernels from these lots with an uncertainty of 1.25% moisture at the 95% confidence level.

V. Discussion and Conclusions

The two measured cavity parameters, shift of resonant frequency and change in Q factor, depend on the permittivity, shape, and volume of an object placed in the cavity, as well as on its orientation and location in the cavity. The ratio of these two measured cavity parameters is, to a great extent, a size-independent function, but its value depends on the shape of the object. Repeating the measurement with the object rotated 90° about the cavity x axis provides another set of data which permits calculation of a ratio of averaged values that is proven to be a shape-independent function. Thus, this ratio can be a direct function of the object permittivity, which can be related to the material density, moisture content, or other characteristic of interest.

Two measurements should be taken on nonuniformly shaped objects rotated by 90° in the resonant cavity or in two identical cavities rotated by that angle. All measurements are relative; i.e., only a difference of two resonant frequencies or two transmission coefficients is necessary. Therefore, high long-term stability of the measuring system is not required.

Available data on nonuniform corn kernels rotated in an S-band cavity show a larger spread when plotted against moisture content than do similar results for more uniformly shaped soybean seeds [7]. The explanation may be twofold:

- Every rotated kernel is measured twice; thus the effect of errors in the measuring system may be doubled when compared with soybeans that are measured only once.
- Linear dimensions of corn kernels (up to 14 mm) were relatively large compared with the half-wavelength (62 mm) at the operating frequency of 3.2 GHz.

Experiments with biological objects are difficult to carry out because the permittivity of the material changes during the measurements (drying), and measurements cannot be repeated exactly. Thus, in spite of precautions taken during the measurements, the accuracy of the data presented in Figs. 2–6 is limited, because of uncertainties in both moisture content and dimension ratio determinations. Small errors in the kernel rotation angle would result in missing the extremum values slightly, which in turn would affect the average value of the parameter. One could speculate, for example, that, when properly averaged, the values of ΔF and ΔT shown in Fig. 5 do not depend on the dimension ratio. Until a final proof is provided, we conclude only that their ratio X is almost independent of the shape of corn kernels. Altogether, the experimental data presented above provide a relatively clear picture of the interactions between the biological objects and the electromagnetic waves inside the cavity. More work needs to be done to develop an analytical expression to describe the effect. However, the technique is accurate enough for practical application, e.g. moisture content determination.

The accuracy of the system calibration for moisture content measurement is affected by an uncertainty of the measuring system, σ_M, consisting of the repeatability of the results for the same kernel of given moisture content, and an uncertainty of the "real" value of the moisture content, σ_c, i.e., the repeatability of the results provided by the standard oven method used for the system calibration. Since both of these uncertainties are of a random character, the uncertainty in using the microwave resonator for moisture determination in corn kernels may be defined as

$$\sigma_s = \pm\sqrt{2\sigma_M^2 + \sigma_c^2}. \quad (7)$$

The uncertainty in moisture content determination by the standard oven method is $\sigma_c = 0.22\%$ moisture and the uncertainties in the resonator measuring system can be determined by differentiation of (6) (for a detailed analysis, see [7]). Assuming an uncertainty in the resonant frequency measurement $\delta f = 0.02$ MHz and an uncertainty in the transmission coefficient measurement $\delta S_{21} = 0.03$ dB, one can calculate $\sigma_M = 0.16\%$ moisture for a single measurement. Therefore, from (7), $\sigma_s = 0.32\%$ moisture content.

The microwave resonant cavity technique has been shown to be a simple, nondestructive, and potentially continuous method for determining the properties (density or moisture content, for example) of single kernels and seeds, regardless of their shape and size variation. The method could be used for other biological objects, including other grains, nuts, and fruits, provided that their volume is small compared to the volume of the resonator. Other types of microwave resonators could also be used for this purpose.

References

[1] S. O. Nelson, "Use of electrical properties for grain-moisture measurement," *J. Microwave Power*, vol. 12, no. 1, pp. 67–72, 1977.

[2] S. O. Nelson and K. C. Lawrence, "Evaluation of a crushing-roller conductance instrument for single-kernel corn moisture measurement," *Trans. ASAE*, vol. 32, no. 2, 1989.

[3] C. V. K. Kandala, S. O. Nelson, and K. C. Lawrence, "Moisture determination in single kernels of corn—A nondestructive method," *Trans. ASAE*, vol. 31, no. 6, pp. 1890–1895, 1988.

[4] H. E. Bussey, "Measurement of the RF properties of materials—A survey," *Proc. IEEE*, vol. 55, pp. 1046–1053, 1967.

[5] R. F. Harrington, *Time-Harmonic Electromagnetic Fields*. New York: McGraw-Hill, 1961, p. 317.

[6] R. A. Waldron, *The Theory of Waveguides and Cavities*. London: Maclaren, 1967, p. 91.

[7] A. W. Kraszewski, T. S. You, and S. O. Nelson, "Microwave resonator technique for moisture content determination in single soybean seeds," *IEEE Trans. Instrum. Meas.*, vol. IM-38, no. 1, pp. 79–84, 1989.

[8] A. W. Kraszewski, S. O. Nelson, and T. S. You, "Sensing dielectric properties of arbitrarily shaped biological objects with a microwave resonator," in *IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 1, 1989, pp. 187–190.

Andrzej W. Kraszewski (M'89) was born in Poznan, Poland, on April 22, 1933. He received the M.Sc. degree in electrical engineering from the Technical University of Warsaw, Warsaw, Poland, in 1958 and the D.Sc. degree in technical sciences from the Polish Academy of Sciences (PAN), Warsaw, in 1973.

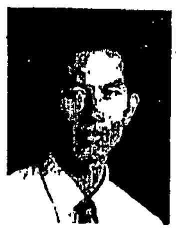
In 1953 he joined the Telecommunication Institute (PIT), Warsaw, Poland, where he did research and development work on microwave systems and components. In 1963 he joined UNIPAN Scientific Instruments, a subsidiary of the Polish Academy of Sciences, as Head of the Microwave Laboratory. In 1972 he became Manager of the Microwave Department of WILMER Instruments and Measurements, a subsidiary of the Polish Academy of Sciences in Warsaw, where he codeveloped microwave instruments for moisture content measurements and control. From November 1980 to December 1986, he was a Visiting Professor at the University of Ottawa, Ontario, Canada, where he was engaged in research on RF and microwave dosimetry. In January 1987 he joined the Richard B. Russell Agricultural Research Center (U.S. Department of Agriculture) in Athens, GA, where he is involved in research on plant structure and composition using electromagnetic fields.

Dr. Kraszewski is a member of the International Microwave Power Institute and the Polish Electricians Association. He is the author of several books on microwave theory and techniques, has published more than 100 technical papers on the subject, and holds 18 patents. He has received several professional awards, among them the State Prize in Science in Poland in 1980.

Stuart O. Nelson (SM'72) was born at Pilger, NE, on January 23, 1927. He earned the B.S. and M.S. degrees in agricultural engineering and the M.A. degree in physics from the University of Nebraska in 1950, 1952, and 1954, respectively, and the Ph.D. degree from Iowa State University, Ames, in 1972. He was awarded an honorary doctor of science degree by the University of Nebraska-Lincoln in 1989.

From 1954 to 1959, he worked as Project Leader in Farm Electrification Research for the U.S. Department of Agriculture at Lincoln, NE, and from 1959 to 1976 served as Research Leader, Electromagnetic Radiation Investigations, Agricultural Research Service, USDA. He was also Professor of Agricultural Engineering and Graduate Faculty Fellow at the University of Nebraska. In 1976, he moved his laboratory to the USDA's Richard B. Russell Agricultural Research Center, Athens, GA, where he is also Adjunct Professor and Graduate Faculty member at the University of Georgia. He is past Chairman of the National ASAE Radiation Committee, a member of the Scientific Advisory Council of the American Seed Research Foundation, and has served as Associate Editor of *The Journal of Microwave Power*. His research areas have included the use of radio frequency and microwave dielectric heating for seed treatment, stored-product insect control, and agricultural product conditioning; studies of the dielectric properties of grain, seed, insects, coal, and minerals; methods of dielectric properties measurement; dielectric properties and density relationships in granular and pulverized materials; and moisture measurement through sensing dielectric properties of agricultural products. These studies have been reported in more than 130 technical journal articles.

Dr. Nelson is a member of Sigma Tau, Tau Beta Pi, Sigma Xi, Gamma Sigma Delta, the American Association for the Advancement of Science, the National Society of Professional Engineers (NSPE), the Council for Agricultural Science and Technology, and the Organization of Professional Employees of the U.S. Department of Agriculture (OPEDA). He is a fellow of the American Society of Agricultural Engineers and the International Microwave Power Institute (IMPI). He has received numerous awards, including the IMPI Decade Award, the NSPE Founder's Gold Medal as 1985 Federal Engineer of the Year, the USDA Superior Service Award, and the Professional Achievement Citation in Engineering from Iowa State University, and he was the 1987 OPEDA Professional of the Year. Dr. Nelson was recently elected to the National Academy of Engineering.



Tian-su You was born in Fujian province, People's Republic of China, on January 10, 1940. He graduated from the Electrical Engineering Department of Zhejiang (Chekaing) University in 1963.

Since then he has been engaged in teaching and research work at Zhejiang University. His research areas include high-energy microwave electronics and the design and development of microwave devices. He is coeditor of *Microwave Principles and Technology* and the author of more than ten articles in professional journals.

Mr. You is a member of the Electronics Institute of China and the Particle Accelerator Institute of China. From September 1986 to May 1989, he was a Visiting Scientist at the U.S. Department of Agriculture's Richard B. Russell Agricultural Research Center, Athens, GA, engaged in measurements of dielectric properties and moisture measurements by microwave techniques.